

Optical Add/drop Multiplexing Performed Using Broadband Transmission Filters and a Narrowband Reflection Filter

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Abstract—We propose and demonstrate the concept of an optical add/drop multiplexing (OADM) device utilising a pair of broadband transmission filters and a narrowband reflection filter. Numerical simulations are used to illustrate transmission filter performance using the classical grating analysis approach, and a discrete inverse scattering grating synthesis technique. We also investigate the power coupling in a cladding-mode coupler device using different chemical compounds as a coupling medium between optical fibres.

Index Terms—Add/drop multiplexing, transmission filters, grating analysis, grating synthesis, cladding-mode coupler.

I. INTRODUCTION

THE rapid growth of dense wavelength-division multiplexing (DWDM) networks across the world, have urged researchers to improve and optimise data transmission, such that it could be faster and more efficient. DWDM networks require components, such as add/drop multiplexers (ADMs), to exhibit a low insertion loss, high channel isolation, and a wide-range wavelength selectivity. It has been shown that add/drop multiplexing can be performed using optical filters, such as short- and long-period fibre gratings [1]. The design of optical filters have attracted many researchers to design low-loss filters using various analysis and synthesis techniques. At present, LPGs contribute a great deal to the high-speed optical fibre communication industry with their guided-to-cladding mode power exchange. LPGs are very beneficial for DWDM networks, since it exhibits low back-reflection, low insertion loss, and are relatively easy to manufacture [1].

The remainder of the paper is organised as follows. Section II provides simulation results for a broadband optical transmission filter using the classical grating analysis method, and Section III illustrates simulation results obtained for a similar broadband transmission filter using an inverse scattering synthesis method. Section IV discusses the proposed design of an add/drop multiplexing device. Numerical results and preliminary results are discussed in Section V, and concluding remarks are presented in Section VI.

II. TRANSMISSION FILTER ANALYSIS BY COUPLED-MODE THEORY

The long-period fibre grating (LPG) structure is the most common form of a transmission filter used in the industry today. The LPG structure has periods in the orders of several hundred micrometers, much longer than that associated with reflection filters (e.g. Bragg gratings) [1]. The induced refractive index modulation of any fibre grating structure along the optical fibre propagation axis can be written as [2]:

$$n(z) = n_a + \overline{\delta n_{core}} \left\{ v \cos \left(\frac{2\pi}{\Lambda} z + \phi(z) \right) \right\} \quad (1)$$

where n_a is the average effective refractive-index, Λ is the grating period, $\phi(z)$ denotes the local phase variation and grating chirp, v is the fringe visibility, and $\overline{\delta n_{core}}$ is the induced index change spatially averaged over the fibre grating period. During the analysis of a LPG structure, the reflection/transmission spectra, dispersion, and time delay properties are calculated, given a known physical grating structure. The coupling between two co-directional propagating modes in a LPG is described by the well-known coupled-mode equations, and is given in Eq.(2) [2].

$$\begin{aligned} \frac{dR(z, \delta)}{dz} &= i\delta R(z, \delta) + iq(z)S(z, \delta) \\ \frac{dS(z, \delta)}{dz} &= iq^*(z)R(z, \delta) - i\delta S(z, \delta) \end{aligned} \quad (2)$$

From Eq.(2) $q(z)$ is the coupling coefficient, and $R(z, \delta)$ and $S(z, \delta)$ are the slowly varying amplitudes of the co-directional propagating modes. The detuning parameter δ for LPG structures is defined as: $\delta \equiv \frac{1}{2}(\beta_{core} - \beta_{clad}^k) - \pi/\Lambda$, where β_{core} is the propagation constant of the core mode, and β_{clad}^k is the propagation constant of the k^{th} cladding mode [2].

When the period of a LPG structure is varied along the fibre axis, the detuning parameter δ and coupling coefficient q varies for different distances along the fibre axis. In our analysis of LPGs, coupling is done to a single cladding mode.

In the case of linearly chirped LPGs the grating period $\Lambda(z)$ can be expressed as [3]:

$$\Lambda(z) = \Lambda_0 \pm \xi \left(z - \frac{L_g}{2} \right) \quad (3)$$

where L_g is the grating length, Λ_0 is the grating period at $z = L_g/2$, and ξ defines the grating chirp. Increasing the grating period along the fibre length indicates negative chirp, whereas decreasing the grating period indicates positive chirp.

III. TRANSMISSION FILTER SYNTHESIS BY LAYER-PEELING ALGORITHM

During the synthesis of a LPG, the LPG structure and physical properties are derived from a desired spectral profile. In this paper the discrete layer-peeling algorithm (DLP) is used to reconstruct a LPG structure from a complex spectral profile [4], [5].

When using the DLP algorithm, the LPG structure is divided into M layers separated by a distance Δz , and the main aim is to obtain the required strength of the instantaneous scattering points ρ_M , given a valid pair of transmission $R_M(z, \delta)$ and cross-coupling $S_M(z, \delta)$ spectra [5]. R_j and S_j are the amplitudes of the fields traversing through a section j of length Δz , where the coupling coefficient $q(j\Delta z)$ is unique for each section j , and is obtained from the coefficients ρ_j using the relation [5]:

$$q(j\Delta z) = -\frac{1}{\Delta z} \frac{\rho_j^*}{|\rho_j|} \arctan(|\rho_j|). \quad (4)$$

The time-domain field coefficients are defined as follows [5]:

$$R_j(\delta) = \sum_{\tau=0}^M r_j(\tau) \exp(i2\Delta z\delta\tau) \quad (5)$$

$$S_j(\delta) = \sum_{\tau=0}^M s_j(\tau) \exp(i2\Delta z\delta\tau)$$

where $\tau = 0, 1, \dots, M$, and the spectral fields $R_j(\delta)$ and $S_j(\delta)$ are periodic with a period $\pi/\Delta z$. The discrete coupling ratio in the grating structure is then simply expressed as $\rho_M = s_M(0)/r_M(0)$. Since the value of ρ_M is known at the final layer, we can now remove this layer and obtain the impulse responses of layer $M-1$ as follows [5]:

$$r_{M-1}(\tau) = \frac{r_M(\tau) + \rho_M^* s_M(\tau)}{\sqrt{|\rho_M|^2 + 1}} \quad (6)$$

$$s_{M-1}(\tau-1) = \frac{s_M(\tau) - \rho_M r_M(\tau)}{\sqrt{|\rho_M|^2 + 1}}. \quad (7)$$

Given a realisable complex spectrum $t(\delta)$ in the interval $-\delta_w/2 \leq \delta \leq \delta_w/2$, the aim is to find the coefficients ρ_j for $j = 1, 2, \dots, M$ [5]. The bandwidth $\delta_w = \pi/\Delta z$ is usually specified, which normally dictates the spatial resolution. The DLP algorithm is based on the fact that the first point of the impulse response must be independent of the ρ_j 's for $j \geq 2$ due to causality, thus $\rho_1 = h(1)$. Since ρ_1 is known, we can simply propagate the fields using the transfer matrices listed

in Ref. [5]. The discrete DLP algorithm can be summarised as follows:

- (1) Specify a physically realisable complex spectrum $t(\delta)$. One should specify a desired cross-coupling spectrum $S(\delta)$, and design an M^{th} order FIR filter using, e.g., windowing. After designing the FIR filter, one should then obtain the polynomial $R(z)$ by a root-finding procedure, or using the discrete Hilbert transform [5], where $R(z)R_*(z) + S(z)S_*(z) = 1$ (the asterisk in the subscript indicate the para-Hermitian conjugate). The z -transforms of the impulse responses $r(\tau)$ and $s(\tau)$, produce the M^{th} order polynomials $R(z)$ and $S(z)$.
- (2) Calculate the coefficient ρ_j .
- (3) Propagate the fields using the transfer matrices from Eq. (6) and Eq. (7).
- (4) Repeat step (2) until the entire LPG structure is reconstructed.

IV. PROPOSED OADM DESIGN

The proposed design of a wavelength-tuneable broadband add/drop multiplexer is presented in Fig. 1. A cladding-mode coupler is constructed (without the need of fusion) using two non-uniform LPGs, which are placed in parallel in close contact ($< 5 \mu\text{m}$) [6]. The non-uniform LPGs are designed and fabricated such that the guided core mode couples to the fifth cladding mode. This particular cladding-mode then propagates in the cladding and a coupling region between the two optical fibres, exciting a similar cladding mode in the parallel placed fibre with a identically inscribed non-uniform LPG.

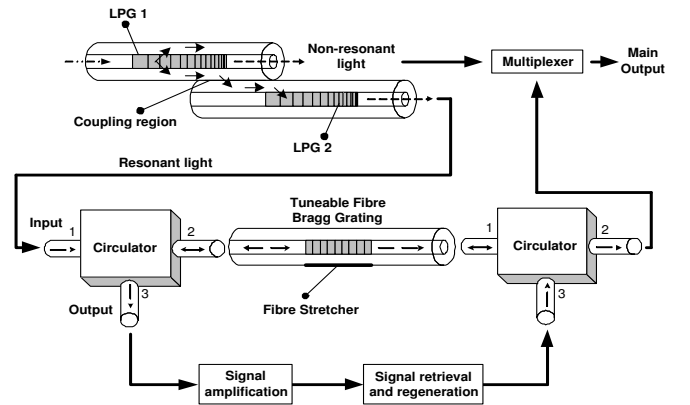


Fig. 1. Proposed design for a broadband add/drop multiplexer designed for DWDM networks.

From Fig. 1 the parallel optical fibres, first circulator, and tuneable Bragg grating performs the demultiplexing operation. The output of the second circulator situated on the righthand side of Fig. 1, can be multiplexed with data propagating in the first optical fibre, using the same cladding-mode coupling configuration used for the demultiplexing part of the proposed OADM device. By tuning the narrowband fibre Bragg grating used in the proposed design, a specific wavelength channel can

be obtained. A low-cost piezoelectric ceramic fibre stretcher (PFS) can be used for the wavelength tuning process. This is accomplished by increasing the length of the FBG by inducing an external voltage to the PFS, resulting in an increase of overall grating period along the fibre axis. However, when a specific wavelength channel is obtained it will be attenuated due to the demultiplexing configuration used, but an erbium-doped fibre amplifier (EDFA) could be used to restore the signal strengths to normal.

V. NUMERICAL AND PRELIMINARY RESULTS

In this section we will briefly discuss numerical results obtained for broadband transmission filters designed using the classical grating analysis and layer-peeling synthesis techniques. We will also discuss some preliminary results obtained from a cladding-mode coupler configuration, after placing two optical fibres containing identical uniform LPG structures in parallel.

A. Simulation Results of a Broadband Transmission Filter Using the Classical Grating Analysis Method

Fig. 2 illustrates the theoretically obtained transmission spectrum of a LPG of 30 mm, where the induced index change Δn_{eff} is 1.2×10^{-3} simulated for different values of grating chirp when the guided core mode couples to the fifth cladding mode. From Fig. 2 the spectrum bandwidth for the uniform and chirped LPG at full-width half-maximum (FWHM) is approximately 13 nm and 72 nm, respectively. The peak transmission loss for the uniform LPG simulated is -10.69 dB, and for the chirped LPG the peak transmission loss is -1.99 dB. The grating period at the centre of the LPG was $464.52 \mu\text{m}$. The parameters used to obtain the data presented in Fig. 2 are similar to those of *Fibercore PSI500 single-mode fibre*, where the numerical aperture $NA = 0.12$, core radius $a_1 = 4.10 \mu\text{m}$, and cladding radius $a_2 = 62.50 \mu\text{m}$.

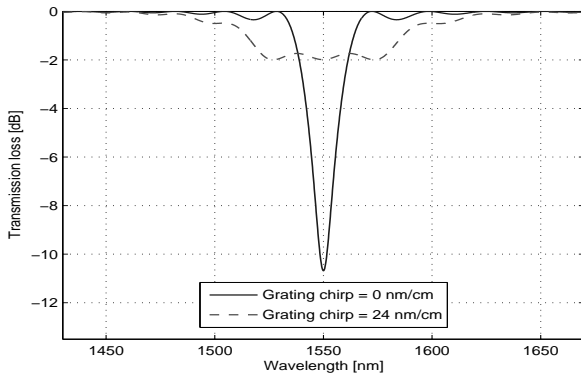


Fig. 2. Transmission spectrum of a uniform and non-uniform LPG simulated for different values of grating chirp.

From Fig. 2 it can be seen that chirping the grating period enables coupling over a larger range of wavelengths. The transmission spectrum broadens as grating chirp increases, and results in a lower value of transmission loss. The transmission

loss would be even lower if coupling was done to lower order cladding modes. The induced index change remained constant throughout the length of the grating, since no apodization profile was applied during the simulations. If apodization was applied, it would be very difficult to obtain a nearly flat-top LPG spectrum, since it would force the spectrum to be narrower. The LPG spectra illustrated in Fig. 2 also illustrate undesired sidelobes in the spectra, which contributes to the amount of dispersion the filter produces. Fig. 3 indicates the dispersion results obtained for the broadband LPG illustrated in Fig. 2.

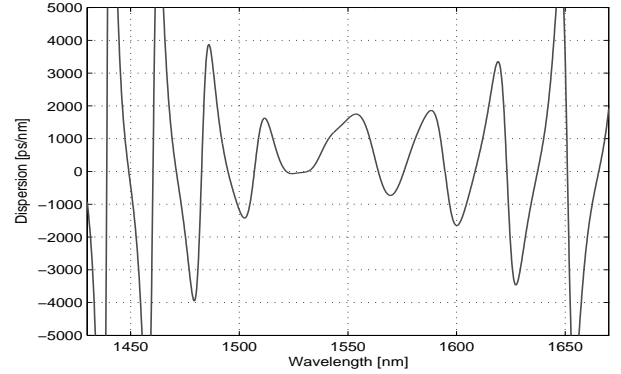


Fig. 3. Dispersion results obtained for a non-uniform LPG simulated using the classical grating analysis method.

B. Simulation Results of a Broadband Transmission Filter Using the Discrete Layer-peeling method

In this section the discrete layer-peeling method is used to design a broadband transmission filter exhibiting a smaller bandwidth to that illustrated in Fig. 2, since it was very difficult to design a LPG structure exhibiting a suitable bandwidth (≈ 11 nm) with the classical grating analysis method in the first place. The target cross-coupling spectrum in the cladding is designed to exhibit a flat-top, nearly rectangular passband described by a "Super-Gaussian" function [7]:

$$t(\delta) = \sqrt{T} \times \exp\left(\left(\frac{\delta}{\delta_{pb}}\right)^{20}\right) \quad (8)$$

where the desired passband width δ_{pb} at FWHM is 11 nm, and the maximum transmission in the passband is $T = 0.99$. The difference in effective refractive index between the two interacting modes is $\Delta n_{eff} = 3.4 \times 10^{-3}$, and the designed wavelength is $\lambda_R = 1550$ nm. The length of the LPG is $L = 30$ mm, the grating period equals $\Lambda = 456 \mu\text{m}$, and the number of layers used to reconstruct the transmission spectrum were $N = 202$. However, the results obtained had to be adjusted accordingly such that it is more practically suited when manufacturing a non-uniform LPG. Fig. 4 and Fig. 5 illustrate simulation results obtained when the ideal index modulation profile results was adjusted to enable the transmission filter structure to be practically realised in an optical fibre.

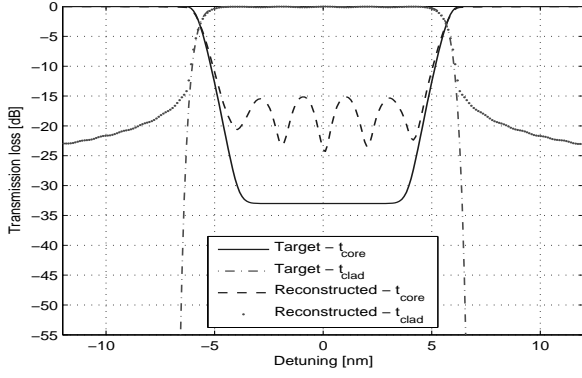


Fig. 4. Target/Reconstructed LPG transmission spectrum for the core mode and cross-coupling spectrum for the cladding mode in logarithmic scale considering practical implementation issues.

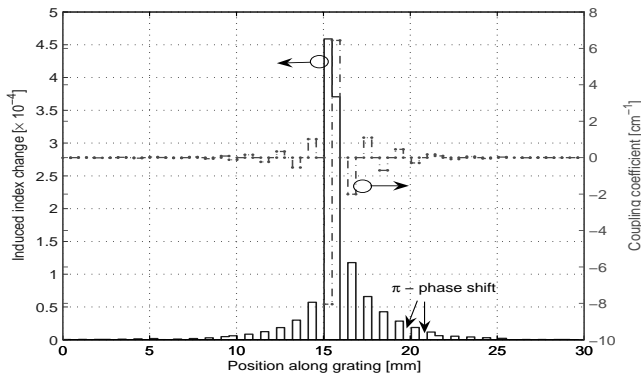


Fig. 5. Reconstructed LPG coupling coefficient (1/cm) and index modulation profile simulated using the DLP method considering practical implementation issues.

From Fig. 4 it can be seen that the core mode transmittance was kept to -24 dB (with a ~ 9.16 dB ripple in the passband of the core mode spectrum), and the cladding mode transmittance did not exceed -24 dB, indicating that this is a very strong transmission filter.

The coupling coefficient illustrated in Fig. 5 did not exceed 14.21 cm^{-1} , the maximum index change obtained was 0.46×10^{-3} , and the grating chirp was 3.66 nm/cm . The ideal LPG structure reconstructed exhibited a sinc-like envelope refractive index variation, and consisted of uniform periods, where there existed a π phase shift at each minimum point of the index modulation profile.

Although the index modulation results obtained in Fig. 5 looks promising, it might still be difficult to implement this refractive index profile in an optical fibre. For example, the index difference between the lowest and second lowest index modulation value in Fig. 5 is 3.25×10^{-7} , and the highest index modulation value is 4.59×10^{-4} . It will take $(4.59/3.25 \times 10^3) \approx 1412$ runs of the fabrication process to manufacture this specific LPG structure, which is very unlikely to occur. Therefore, the index modulation profile must be optimized

further to ease the fabrication of such a transmission filter. By using the flip-flop optimisation method [8] in conjunction with the DLP method, even better index modulation results can be obtained.

Basically, the grating period still remains uniform throughout the grating length, but the index modulation values are changed to simplify the LPG fabrication process. When the flip-flop method was used, the initial design for the transmission filter consisted of grating periods exhibiting either a high refractive index, or a low refractive index. Before optimising the index modulation results, a merit function was evaluated that represents the overall performance of the initial design. We started to set the refractive index of the grating periods, one period at a time, to exhibit either a high or low index change value, with all the other grating periods remaining unchanged [8]. We calculated the merit function for both cases, and the index change value that resulted in the best performance was retained and used in further calculations. The refractive index change values was changed in the direction from the beginning of the LPG until the end. Fig. 6 illustrates the transmission spectrum obtained for the core mode and cladding mode after implementing the flip-flop optimisation scheme in conjunction with the DLP method.

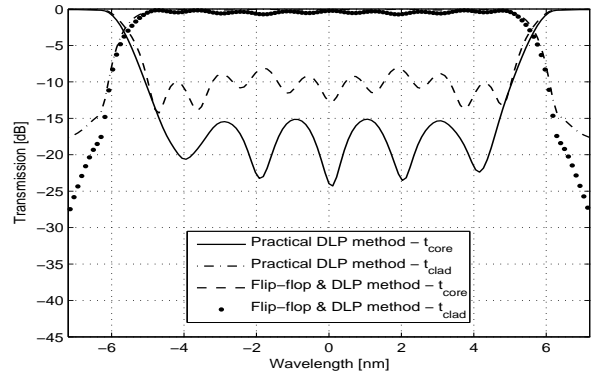


Fig. 6. LPG transmission spectrum for the core mode and cross-coupling spectrum for the cladding mode in logarithmic scale for results obtained with the practical DLP method and flip-flop optimisation method.

The optimised index modulation results are illustrated in Fig. 7. The index modulation results was obtained after 10 iterations of the flip-flop method, in 150.6 seconds. The optimised results illustrates that the transmission filter has a high transmission loss (> 8 dB), and exhibits a much simpler index modulation profile.

Fig. 8 illustrates that the dispersion for the optimised filter illustrated in Fig. 6 is small when the LPG is reconstructed using the DLP method, but increases when the filter structure results are adjusted for practical implementation, especially when the flip-flop method is used in conjunction with the DLP method. The peak-to-peak dispersion value in the passband for the optimised LPG structure, was approximately 12 times lower than the dispersion value obtained for the chirped LPG simulated in Fig. 2.

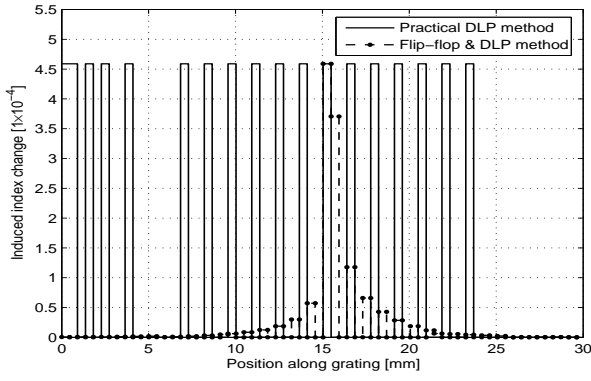


Fig. 7. Index modulation profile results obtained using the practical DLP method and flip-flop method.

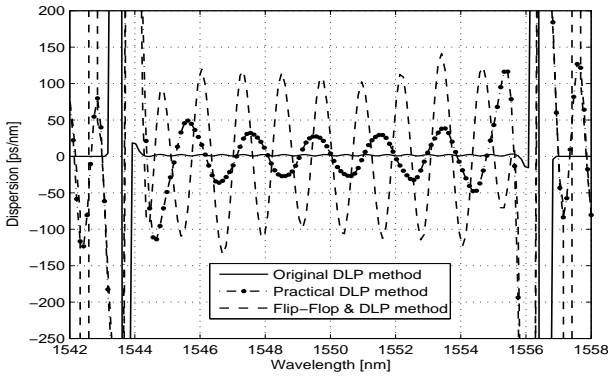


Fig. 8. Optimised broadband filter dispersion results obtained using the DLP method and flip-flop method.

C. Preliminary Results

We investigated the concept of core-mode-cladding-mode coupling, which is necessary for the demultiplexing part of the OADM device illustrated in Fig. 1. To accomplish this we started to manufacture two identical LPGs in the same fibre core spaced 125 mm apart. A KrF excimer laser ($\lambda = 248$ nm) was used in conjunction with an amplitude mask, to fabricate the uniform LPGs in PS1500 single-mode fibre. The pulse repetition frequency of the laser was 20 Hz during grating fabrication, and the energy per pulse used to induce the index changes in the fibre core was 380 mJ. An *Ocean Optics LS-1 tungsten-halogen* broadband source was used as light source when measuring spectrum output. Fig 9 illustrates the spectra obtained from a *Yokogawa AQ6317C optical spectrum analyser* (OSA) during the fabrication of the identical LPG structures.

From Fig. 9, after the first LPG is fabricated the transmission loss is approximately -12 dB at 1550.50 nm, when coupling is done to the fifth cladding mode. The reason why there is a dip in the transmission loss after the second LPG was written, is because after light couples from the first LPG core to the cladding, the cladding mode will propagate until it is in the region of the second LPG, whereby the light couples

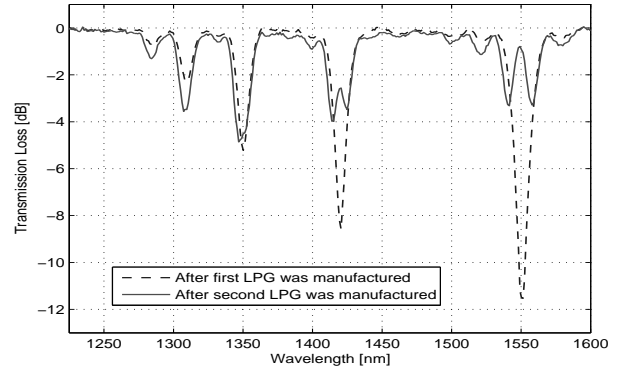


Fig. 9. Measured transmission spectrum after the first and second LPG were fabricated in PS1500 single-mode fibre.

back to the fibre core, resulting in very little light to propagate in the cladding after the second grating. The transmission loss measured at 1550.50 nm after the second LPG was written, was approximately -0.9 dB.

After the identical LPGs were written, we proceeded to build the core-mode-cladding-mode coupler similar to the one proposed for the OADM illustrated in Fig. 1 and 10.

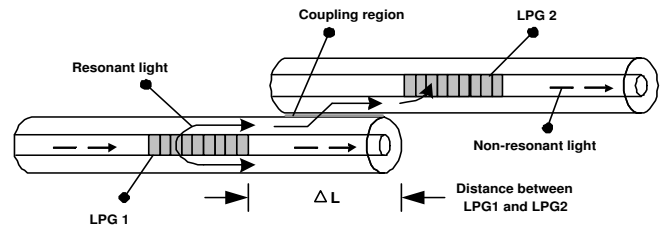


Fig. 10. Experimental set-up for the investigation of core-mode-cladding-mode coupling between parallel optical fibres containing identical LPGs.

We investigated the coupling of light between the two optical fibres by using different chemical compounds, namely Propanol and index-matching gel, for the coupling region between the fibres. The chemical compounds are used to expand the coupling region between the optical fibres. The losses are excessive if air act as the coupling medium between the optical fibres [9]. A *Photonic wavelength-tuneable laser diode* source was used as light source for the measurement of light power coupled from one fibre to the next, and a *Agilent 8163A lightwave multimeter* was used to measure the coupled light power. The laser diode source power was set to 1 mW and the wavelength set to 1550.50 nm, since the maximum transmission loss of the LPGs occurred at this particular wavelength. Fig. 11 illustrates results obtained for power coupling occurring in the cladding-mode coupler device illustrated in Fig. 10, when the distance between the first and second LPG is decreased, and different chemical compounds are used as a coupling medium between the optical fibres.

It can be seen from the results that the index-matching gel is the more superior chemical compound used to improve the coupling region between the optical fibres, resulting in a peak

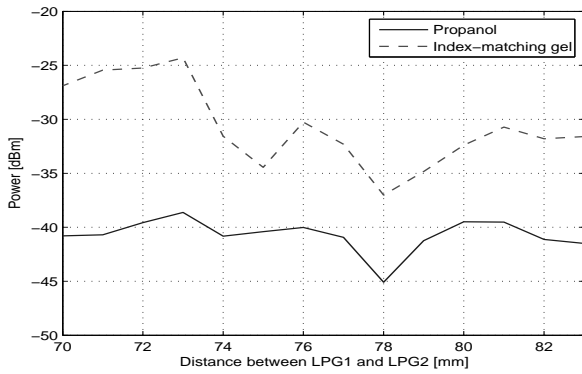


Fig. 11. Measured power coupling between parallel optical fibres using different chemical compounds as a coupling medium.

coupling power of -24.31 dBm when the distance between the LPGs are set at 73 mm. When the LPGs were placed closer, the power coupling results did not improve. Fig. 12 illustrates the measured spectra from the OSA, for the weakest and strongest power coupling achieved in the cladding-mode coupler device.

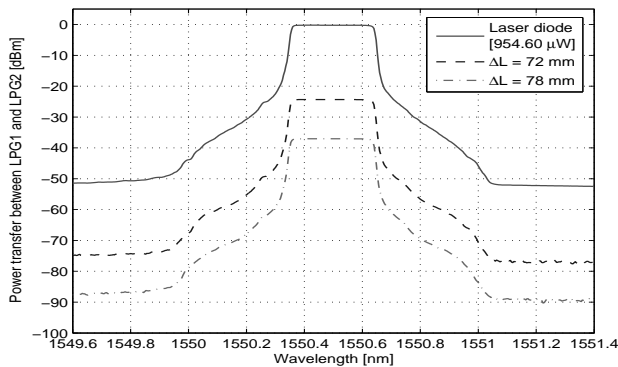


Fig. 12. Power spectra obtained for the weakest and the strongest power coupling between parallel optical fibres.

From Fig. 12 it can be seen that the power difference between the strongest coupling between the fibres, and the laser diode source remains significant, but there is sufficient light transfer between the parallel optical fibres. The laser diode power sent through the first optical fibre was actually $954.60 \mu\text{W}$, due to optical connector and link losses in the experimental set-up. The results obtained for the cladding-mode coupler incorporating uniform LPGs are very encouraging, and this coupling mechanism shows great promise for the future.

VI. CONCLUSION

We have shown that the DLP technique is much superior to the classical grating analysis technique, in designing broadband transmission filters for application in DWDM network systems. The DLP method allows transmission filters to be reconstructed fast and efficiently, but results in index modulation profiles that are difficult to implement in practise. Using the flip-flop optimisation method in conjunction with the

DLP method, results in much simpler LPG index modulation profiles, which may be implemented in the LPG fabrication process. However, the flip-flop method does not require a complex initial design, and has a rapid convergence. A cladding-mode coupler consisting of two parallel optical fibres, each containing identical uniform LPGs, has been constructed, and results have shown that light transfer between the optical fibres is sufficient. When index-matching gel was used as a coupling medium between the parallel optical fibres, light transfer was improved, as in the case when propanol was used as coupling medium. The results obtained thus far looks very promising, and it is expected that if a OADM device is constructed in a manner as presented in this paper, it would result in a device exhibiting reasonable insertion losses and channel cross-talk, and would ultimately reduce the cost in developing a low-cost add/drop multiplexing device.

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